SUSTAINABLE SHIP SPEED CRITERIA FOR DIFFERENT SEA STATES WITH EXAMPLE ON CONTAINER SHIP

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ABSTRACT

The aim of this paper is to show application of operational criteria that are used to select sustainable speed for different sea states. Also is given overview how seamen feel operational criteria and which is sustainable speed for some sea states in real life.
Selected criteria are bow accelerations, slamming and green water occurrence.
Large container ship is used as example to show application of operational criteria on North Atlantic sea environment. Operability polar plots are calculated and selected for interesting sea states. Method used for this calculation is 3D panel method.
In conclusion are given advantages and disadvantages of existing criteria and guidelines for future research.

KEY WORDS

operational criteria seakeeping sustainable speed North Atlantic sea states container ship

1. INTRODUCTION

Maritime transport has a great role in global transport of goods and products so ship operations have to be safe and optimized. Safety and optimization lead to promptness and accuracy. Ship maneuvering is very important, especially on rough sea. Maneuvering on calm sea is, largely, a routine. Problems occur when environment conditions are extreme. Loads on ship structure are on high level in extreme environment conditions. Safe operability of ship, in extreme sea conditions, is questionable. In those cases ship maneuvering has to be done such as speed reduction and/or changing of wave heading direction. Knowledge of wave loads and sustainable speeds simplifies decisions to seafarers.
Question is what that knowledge should include and how seafarers have to react in rough weather. First of all, knowledge of operability criteria is necessary. Criteria considered in this paper are slamming, deck wetness and vertical acceleration on bow. Limiting values of operability criteria, for each type of ships, show if operability margin was overshot.
Influence of criteria limiting values are shown on example of 9200 TEU container ship by polar plots and operability

diagram. Those diagrams and plots are useful to seafarers for safe and optimum ship maneuver in rough sea.

2. CRITERIA FOR SHIP OPERABILITY IN ROUGH SEA

Seakeeping studies are used to find out ship response on different sea states. The resulting response is validated by operability criteria limiting values. Operability limiting values are border between acceptable and unacceptable phenomena. Phenomena considered in this paper are slamming, deck wetness and vertical acceleration on bow.

2.1. Slamming

Slamming phenomena occurs if bow of the ship emerges out of the sea at certain speeds and certain sea states.
Re-entry leads to impact between flat bottom in the forward part of the ship and the sea surface. Result of impact is the suddenly developed force that produces transient vibrations of the hull, known as whipping. Seafarers can clearly feel slamming because vibrations of the hull complicate normal activity on board such as steerage, navigation, cargo control, etc. Slamming also complicates repose of the crew which is very important for ship safety. Emerging of the bow is result of relative motions between sea surface elevation and ship motion components such as heave and pitch. Slamming will occur if relative motion is larger than draft of the ship and if relative velocity is larger than critical velocity (Ochi & Motter 1974).
Ochi defined a critical relative velocity of the bow as:

$$v_{cr} = 0.093\sqrt{g \cdot L} \quad (1)$$

where g is acceleration of gravity and L is length of the ship.
Limiting value of slamming is usually given in term of probability. Probability of slamming is given as:

$$P_{slammning} = e^{-\left(\frac{D^2}{2m_{0r}} + \frac{v_{cr}^2}{2m_{0v}}\right)} \quad (2)$$

where D is draft of the ship, m_{0r} is zero-th spectral moment (variance) of relative motion, m_{0v} is zero-th spectral moment or variance of relative velocity.

2.2. Deck wetness

Appearance of deck wetness can happen at any place on the ship where freeboard is not high enough. It usually occurs on fore part of the ship when relative motion of the bow exceeds height of the freeboard on bow. Deck wetness can cause equipment damage and loss of the cargo, especially on container ships.
This type of seakeeping criteria is the most recognizable amongst seafarers because it is visually attractive. Probability of deck wetness is given as:

$$P_{deck\,wetness} = e^{-\left(\frac{f_x^2}{2m_{0r}}\right)} \quad (3)$$

where f_x is freeboard on section x of the ship, m_{0r} is zero-th spectral moment for relative motion.

2.3. Vertical acceleration at forward perpendicular

Absolute vertical acceleration on bow can cause damage of the structure or equipment. Furthermore, excessive accelerations could disturb seafarers in their normal activity on ship. Inexperienced or not adapted seafarers feel seasickness that leads to impossibility of normal work and deficit of safety on ship. Vertical accelerations on the bridge are also very important for seafarers but are not taken under considerations when calculating operability.

3. APPLICATION OF OPERABILITY CRITERIA ON 9200 TEU CONTAINER SHIP

Characteristics of 9200 TEU container ship:

Lpp	335m
B	42.8m
T	13.17m
V	25kn
Capacity	9200 TEU

Safety of the seafarers is the most important thing. Second point is safety of the cargo. To satisfy safety criteria seakeeping features of the ship have to be on satisfactory level. Seakeeping features can be described in many ways. The easiest way for seafarers and companies is by sustainable speed on rough sea states. Sea states are described by wave heights and periods. Sea states describing rough weather are given for North Atlantic sea environment according to the IACS recommendation Note No.34 (Figure 1.).

Hs/Tz	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	SUM
0.5	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	3050
1.5	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	22575
2.5	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	23810
3.5	34 .9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	19128
4.5	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	13289
5.5	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	8328
6.5	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	4806
7.5	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	2586
8.5	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	1309
9.5	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	626
10.5	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	285
11.5	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	124
12.5	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	51
13.5	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	21
14.5	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	8
15.5	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	3
16.5	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	1
SUM:	2091	9280	19922	24879	20870	12898	6245	2479	837	247	100000

Figure 1. IACS recommendation Note No.34

3.1. Methodology of calculation

Seakeeping features are calculated for different ship responses in short-term sea states based on the response amplitude operators (RAO). 3D panel method is employed for computation of RAOs, while 2-P Pierson–Moskowitz wave spectrum is used for short term spectral analysis.

RAOs are calculated using state-of-the-art seakeeping software Hydrostar (Bureau Veritas 2010) while results are post processed using program Starspec (Bureau Veritas 2010). Calculations are based on 3D panel method and linear potential theory.

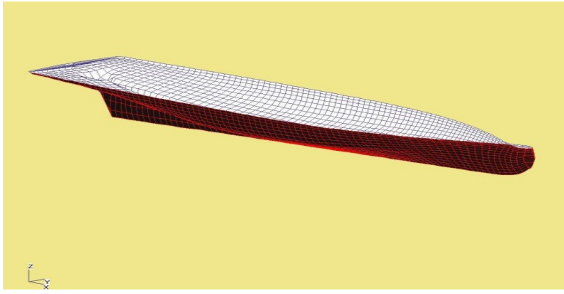

Figure 2. 9200 TEU hydrodynamic model in Hydrostar

Response amplitude operators are calculated at forward part of the ships for:

- relative vertical motion,
- relative vertical velocity,
- absolute acceleration.

All three RAOs are calculated for four speeds:

$$\tfrac{1}{4}v = 3.125m/s$$

$$\tfrac{1}{2}v = 6.430m/s$$

$$\tfrac{3}{4}v = 9.645m/s$$

$$v = 12.460m/s$$

For assessment of ship operability in rough sea states, ship response is calculated by Starspec software for spectral analysis. In this calculation only short term ship response is investigated because of assumption that rough sea state represents storm that lasts a few hours (short term). 2-P Pierson–Moskowitz wave spectrum formulation is used for short term spectral analysis. One of the results of spectral analysis is zero spectral moment m_0, from which significant response may be determined as:

$$R_S = 4 \cdot \sqrt{m_0} \tag{4}$$

where R_S is significant response (double amplitude). Significant response is calculated for each combination of RAO and speed of the ship.

3.2. Limiting values of operability criteria

Limiting values are margin between acceptable and unacceptable significant responses.

Table 1. Limiting values used in operability calculation

Limiting probability of slamming	0.0112
Limiting probability of deck wetness	0.05
Limiting RMS of vertical bow accelerations	0.108g

3.1. Results

Practical results, useful to seafarers, are generated in program Starspec. Calculations carried out in Starspec connect significant response and limiting values of operability criteria. Results are shown in two ways:

- operability polar plots,
- operability diagram.

Computing is provided for bow heading sea.

Operability polar plots (Figures 3.-6.) show which navigating azimuth and which speed is sustainable for each sea state. Sea states are given in scatter diagrams. For calculation presented in this paper North Atlantic scatter diagram from IACS recommendation Note No.34 is used. Each sea state has its own operability polar plot.

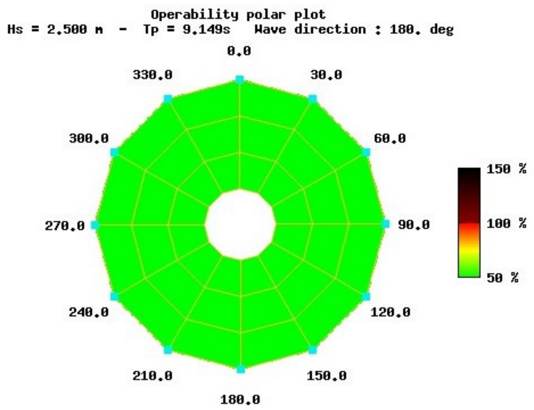

Figure 3. Polar diagram for four sppeds, H_s=2.5m, T_p=9.149s, heading=180°

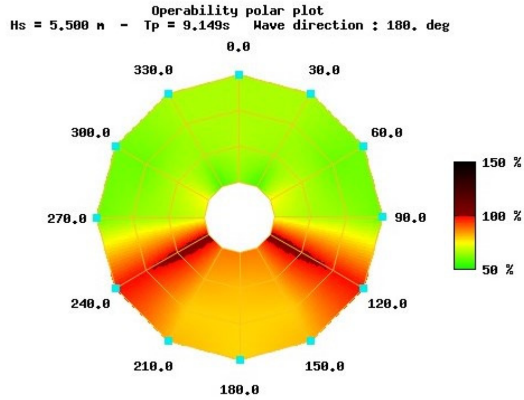

Figure 4. Polar diagram for four sppeds, H_s=5.5m, T_p=9.149s, heading=180°

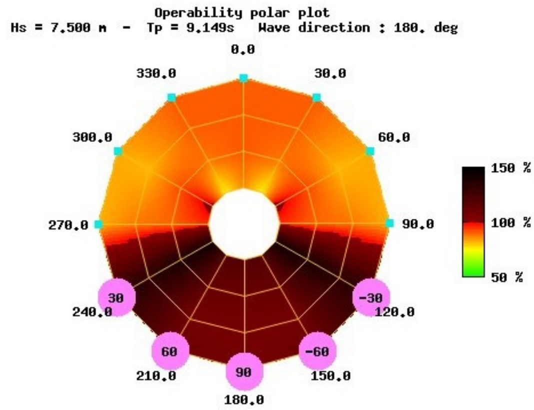

Figure 5. Polar diagram for four sppeds, H_s=7.5m, T_p=9.149s, heading=180°

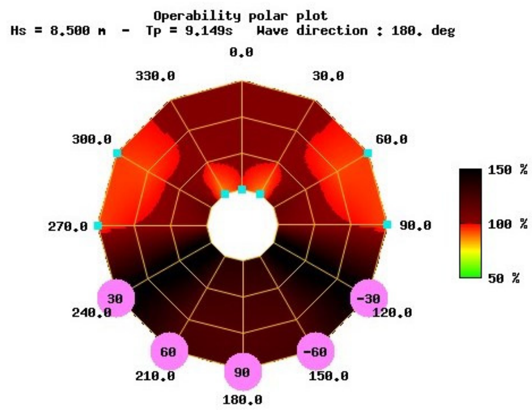

Figure 6. Polar diagram for four sppeds, H_s=8.5m, T_p=9.149s, heading=180°

Figures 3, 4, 5, 6 show operability polar plots for same wave period (T_p=9.149s), but for four different wave heights (H_s=2.5m, H_s=5.5m, H_s=7.5m, H_s=8.5m). 180^o means that ship is heading waves with bow.
It is obvious that for seas state on Figure 3 no maneuvering has to be one.
For sea states shown on Figures 4, 5 and 6 maneuvering has to be done. Maneuvering activities are speed reduction (or acceleration) and/or azimuth change. Shown plots are taken from list of plots derived for a bunch of sea states because all plots can not be shown in paper. Reason for showing this sea states are great probabilities of their appearance in North Atlantic.

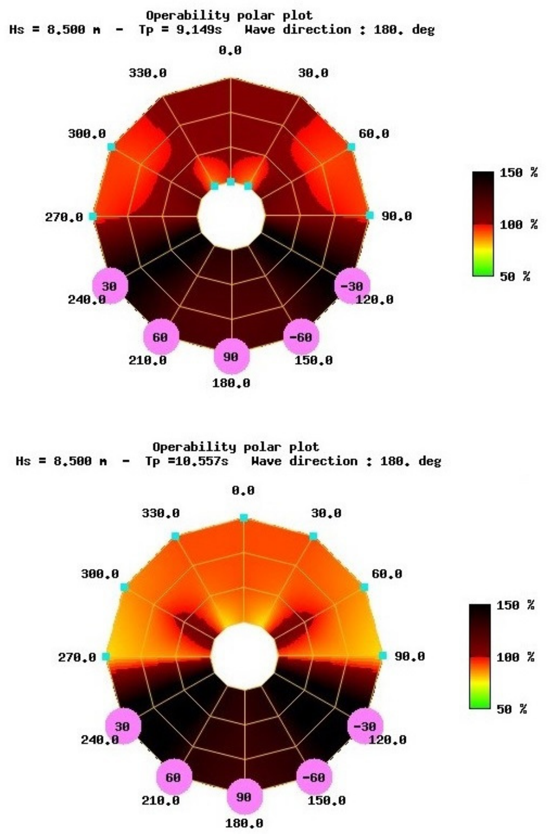

Figure 7. Comparison of two polar plots, same wave height, different periods

Figure 7 shows comparison of two operability polar plots, wave height is same but wave period is different.
Because of correlation between wave period and length of the ship, second polar plot shows better conditions of operability.
Conclusion for seafarers who navigate on considered 9200 TEU container ship is that wave period of 9.149s is more critical than wave period of 10.557s. In IACS recommendation Note No.34 is shown that sea state of H_s=8.5m and T_p=10.557s has higher probability of appearance.

Operability polar plots are not user friendly for seafarers. More useful could have operability diagram and speed diagram.
Operability diagram (Figure 8) shows appropriate maneuvers for navigation on different sea states.

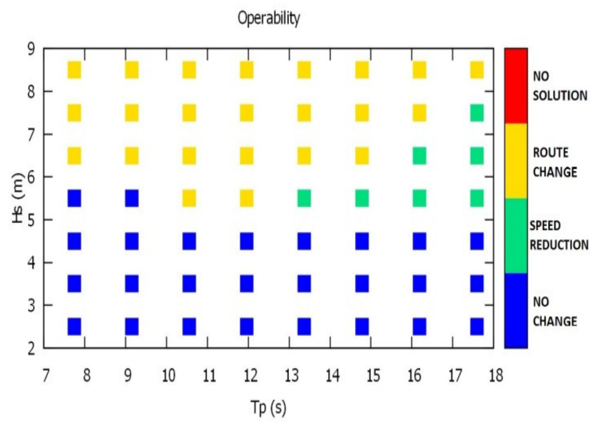

Figure 8. Operability diagram for 9200 TEU container ship

Interesting maneuvers are speed reduction ane route change. Operability diagram groups all polar plots for all default sea states in one place.

4. CONCLUSION

Results presented in this paper could be useful to seafarers, companies and ship owners.
Benefit for seafarers is that with operability diagram decisions, for speed reduction or for azimuth change, are easier to make. Those decisions have influence on:

- quality of life on the ship,
- less fear and stress of the crew,
- increased confidence of the crew,
- better performance of everyday service.

Benefit for companies that are responsible for cargo:

- cargo is much more safe.

Benefit for ship owner:

- ship construction is not exposed to maximum loads,
- ship equipment is more safe.

Benefit for all three groups is that safety is on higher level which is the most important thing.

Results, also, have some uncertainties.
Understanding and reading of presented diagrams depend on the experience of seafarers because recognition of sea states is subjective.
Calculation has uncertainties because depends on methods and theories that does not include all conditions. Also were provided only for bow heading seas. Other directions would be interesting for seafarers, like including side heading waves. Comparison of calculated results and experience from real service would be priceless for this field.

Recommendation of authors is training on simulators for seafarers. In that way they will get use to maneuvering on rough sea and practice will make their decisions safer and faster. Common contact between experienced seafarers and naval architects would, also, be priceless.
The mentioned field is of interest for both naval architecture and maritime research disciplines which will lead to better incorporation of reaction of seafarers on rough sea maneuvering in ship structural design.

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